BELLCOMM, INC.

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FINAL REPORT - TASK 28
"DATA PROCESSING FOR ADVANCED MANNED MISSIONS"

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ABSTRACT

This report summarizes the work accomplished under Bellcomm Task 28, "Data Processing for Advanced Manned Missions." The task resulted in the definition of an overall flow of data in space and on the ground for a planetary flyby and two earth-orbital missions. It also evaluated advances in aerospace digital computers and defined functional requirements for computers on advanced manned missions. A brief summary of each document issued under Task 28 is given in the Appendix.

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FINAL REPORT - TASK 28
"DATA PROCESSING FOR ADVANCED MANNED MISSIONS"

1.0 INTRODUCTION

Task Order 28, "Data Processing for Advanced Manned Missions," was concerned with both the overall flow of data and the role of the spaceborne computer within this flow. The task had three major objectives:

1. To define the overall flow of data, identify important tradeoffs and problem areas, and prepare data flow charts for various advanced missions;

2. To evaluate advances in digital computer technology for application to advanced spaceborne computer systems;

3. To define functional requirements for spaceborne computers on advanced manned missions.

This report summarizes the results of the study in the three areas listed above. A brief summary of each document issued under the Task is included in the Appendix.

2.0 OVERALL FLOW OF DATA

The study of the overall flow of data for advanced manned missions was divided into a study of spaceborne data flow and a study of ground-based data flow. The interface between the two, namely spacecraft-earth communications, was treated as a third study area.

Three types of advanced missions were considered as examples for these studies: a Mars flyby mission; an earth-orbital mission emphasizing earth resources and meteorology experiments; and an earth-orbital mission emphasizing astronomy experiments. Each was assumed to take place for the first time in the mid-70's. The missions are defined in more detail in Reference 1.

2.1 Flow of Data in Space(1)

It was concluded that the above types of advanced manned missions will generate vast amounts of data, mostly in the form of pictures. Generation rates in the range of 1-30 megabits/sec, and total data in the range of 10^{14}-10^{15} bits per mission will be returned to earth by a combination of transmission and physical return.

Some data will be stored on board a spacecraft for transmission at a later time, for use on board, or for return with the crew. Most of the bits stored will be in the form of developed film. Nevertheless, large bulk memories for storing data electrically will also be required--about 10^7-10^8 bits for storage of computer programs and tables, and 10^9-10^{11} bits for storage of data collected during the mission.

Transmission rates on the order of 1 megabit/sec for a Mars flyby mission and 20 megabits/sec for an earth-orbital mission will probably be feasible in the mid 70's. Given these high rates, there should be no problem in transmitting non-imagery data to earth. However, if large numbers of images are to be returned from deep space missions, compromises will have to be made among the number of pictures returned, their quality, and the delay in delivering them to users. For example, a high resolution picture containing 2×10^{10} bits takes 5.6 hours to be transmitted at 1 megabit/sec. Sending a single frame, commercial quality TV picture of the same scene ($\sim 2 \times 10^6$ bits) would take only 2 seconds. The latter alternative allows near-real time recovery by sacrificing resolution.

Another alternative is the use of formal data compression techniques. Unfortunately, the bulk of the data on the missions considered would consist of experiment photographs (and other images) with poorly known statistics or with a high premium on saving new or unusual features. High resolution photographs of planets are examples. Formal compression techniques cannot be applied to these data without risk of losing significant information. However, after a number of uncompressed images are processed on board or on earth, a compression technique might be chosen for the remaining images. There will also be some imagery experiments (e.g., stellar surveys) and operational pictures (e.g., crew movements) which will better lend themselves to compression. It was, therefore, concluded that automatic data compression techniques would be used on advanced missions, but they must be alterable in flight if they are to be used for the bulk of the data.

The crew's ability to do high-level information processing should also be used to reduce data transmitted. The score of their activities can range from "simple" tasks such as selecting parts of pictures for transmission, to the complex processes of interpreting and generalizing on experimental results. However, all of the data compression burden cannot be placed on the crew because they can be overloaded by even such "simple" tasks as picture selection. For example, manually scanning every picture collected on the model earth resources mission used in this study would require 45 man-hours/day!

Data compression is only one of many tasks which will be included in onboard data processing on advanced missions. Several others are discussed in Section 4.0.

2.2 Spacecraft-Earth Communications

Ideally, one would like to send all data collected on the mission to earth in real time. Because this is impractical with the present state of technology, one attempts to maximize data rates and total bits transmitted, subject to the basic constraints of spacecraft weight and dollar cost.

A study(3) performed within Bellcomm (but outside of Task 28) showed that a 1 megabit/sec downlink is feasible at planetary encounter on a Mars Flyby Mission.* At least a 1 megabit/sec capability would be available for more than 90% of the mission. This is equivalent to several commercial-quality TV pictures per minute, or one very high resolution picture (with $\sim 10^{11}$ bits) per day. At least half and possibly all of the data collected on the model Mars Flyby Mission could be transmitted before the spacecraft returns to earth.(1)

Transmissions would be made to one of three Deep Space Network (DSN) sites. If more than ~100 kilobits/sec were to be forwarded in real time from the DSN sites to a central processing site, communications satellites serving as ground-air-ground relays would be required. (They might even be desirable for lower rates.) The bulk of the data would be stored at the DSN sites and physically forwarded at a later time.(1)

*This assumes a 20-30 ft. antenna on board the spacecraft, 363-145 watts transmitted output power, and a 210 ft. Deep Space Network antenna receiving at earth.

For low earth-orbital missions, downlink capacity as high as 20 megabits/sec would be feasible. This capacity would allow real-time TV transmissions of nearly commercial quality. Since TV would be used only sporadically, the same channel could be used and would be large enough for all other mission purposes. An omnidirectional spacecraft antenna with 10-20 watts output power could be used with essentially the present Manned Spaceflight Network (MSN) to provide the 20 megabits/sec rate, but with only 20% ground coverage.(2)

To obtain 100% coverage, three synchronous satellites would be required as links between the spacecraft and ground. The spacecraft would require the equivalent of a 15 ft. parabolic antenna and 40-70 watts output power. Nearly all data collected on the earth resources mission could be transmitted using this system. The use of synchronous relay satellites would also allow the use of a central receiving station on the ground.(1,2)

2.3 Flow of Data on the Ground(1)

Data management functions on the ground will be similar to those for Apollo. Rates and volumes will be much larger. Experiment data processing, especially for pictures, will be vastly increased, and there will be a requirement to process data from two or more simultaneous missions.

The overall ground processing and routing scheme will depend heavily on whether or not communications satellites will be available for routing data to a centralized mission control center. This is true for deep space as well as earth-orbital missions. If communications satellites are not used, a decentralized system somewhat along the lines of the present Apollo network is logical. Regardless of which scheme is used, the state of computer technology is expected to be adequate to handle mission operations, except for the unlikely possibility of having to do complex picture processing in real time. The major ground data processing problems relating to mission control are thus likely to be more of organization and efficient use of resources than of technical feasibility. Typical questions will be: should each mission use a dedicated computer system or time share a larger system; and, what should be the division of responsibility for experiment control between NASA and principal investigators?

Processing the collected data is quite another matter. Again it is mainly the pictures at question. Unless there are surprisingly large advances in computer technology and in our knowledge of how to automatically retrieve information from pictures, it is doubtful that the ground processing could keep up with the rate of data collection from some classes of earth-orbital missions. Of course, it is easier to compromise the depth and time period of experiment data processing than of mission safety data. Nevertheless, it will be increasingly important to match mission objectives to ground data processing resources, both human and machine.

3.0 SPACEBORNE COMPUTER TECHNOLOGY

In order to evaluate advances in computer technology which might be applicable to advanced manned missions, it is necessary to understand what the state-of-the-art of aerospace computers is today and how it has evolved. It is also important to understand the evolving role of these computers within overall avionics systems.

To achieve these goals, a canvass by mail was conducted of all known aerospace computer manufacturers. The canvass requested information on the manufacturers' latest machines. Discussions were held with various branches of NASA and the DOD to determine new applications of aerospace computers and to learn how they are being integrated within larger systems.* Visits were also made to Navy branches having shipboard computer applications related to those in spacecrafts. A literature search on aerospace computer technology was conducted and was supplemented by direct discussions with some computer manufacturers and by attendance at technical society meetings.

3.1 State-of-the-Art of Aerospace Computers(4)

The results of the above activities show that some sharp changes have occurred in aerospace computers over the five year period ending in 1967. The fastest available add time has decreased by a factor of six, to 2 μsec; the fastest available multiply times have decreased by the startling factor of forty, to 6 μsec. Nevertheless, computers are still being produced with a fairly wide range of characteristics, reflecting the variety of applications and budgets for which they are intended. One major trend is toward aerospace computers which look more and more like ground-based machines. Multiple formats for instruction words, instruction sets compatible with ground-based machines, and memory hierarchies are examples of this trend.

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*See trip reports listed in the Appendix for further details on these meetings.

3.2 Recent New Applications for Aerospace Computers

Recent new applications of aerospace digital computers include tasks which have been taken over from analog systems in order to obtain more precision, to allow more complex processing, or to increase reliability. This "takeover" phenomenon is especially prevalent in aircraft and ships for such functions as fire control, autopilot, guidance and navigation, and display-driving. It has also occurred in space vehicles for autopilot, guidance and navigation, and pointing and holding functions.

Another source of new applications is simply the expansion of previous applications which have proven successful. Thus, limited driving of simple displays has expanded into control of integrated displays; and guidance and navigation have become increasingly sophisticated and more accurate.

The third source of new applications are those which become feasible or economical to automate only with the use of digital computers. For example, much work[5,6] is being performed at Goddard Space Flight Center to increase the amount of experiment data processing which can be performed in space, and to make the assignment of channels and sampling rates more flexible by carrying telemetry formats as inflight programmable software.[5] Another application of this kind upon which the DOD is relying heavily, is automated testing and diagnosis for their increasingly complex electronics, especially computers themselves.

3.3 Configurations of Aerospace Computer Systems

Now that aerospace computers are becoming more and more powerful, and the number, variety, and flexibility of off-the-shelf machines is increasing, the aerospace industry is faced with questions similar to those the ground has had for years: Namely, how shall we select our overall computer system configuration? Should we decentralize, using function-oriented machines, or put all the functions into one large (computer system) basket? Should we use multiprocessors, multicomputers, or completely independent machines? Should we use redundancy at the component, module, or computer level?

From the research conducted under Task 28, it is apparent that there are few if any dominating trends which might indicate answers to these questions. There are examples of the complete range of heavily centralized to heavily de-centralized avionics systems flying today. The prime reason for this situation is the lack of satisfactory quantitative tools to search for answers.

Virtually no aerospace computer systems configurations are optimized; most are determined by a combination of logic, intuition, and personal biases, with the goal of finding some workable configuration. Management considerations also play a major role in configuration selection. The problems inherent in managing large software systems create pressure toward decentralized hardware and software. Splitting avionics systems components among several contractors also makes a decentralized system easier to integrate than one in which all parties share common computer hardware and software. On the other hand, there is a proliferation of paperwork and management which is attendant to increasing the number of identifiable systems.

It is entirely appropriate that management problems should be considered. However, in the absence of being able to quantify technical aspects of the problems, and while waiting for technological advances to alleviate them, the management considerations have become dominating. Research into quantifying gross system configuration tradeoffs, including hardware-software tradeoffs, is greatly needed.

4.0 FUNCTIONAL REQUIREMENTS OF SPACEBORNE COMPUTERS[7]

The definition of functional requirements for spaceborne computers for the three previously mentioned advanced manned missions was a goal of Task 28. "Functional requirements" means the tasks which the onboard computer system would be required to perform, regardless of its configuration.

In the Apollo Program, spacecraft computers are used for guidance, navigation, and attitude control. To perform these functions they also drive simple displays, and accept keyed inputs from the crew, and telemetered inputs from the ground. These functions will all be expanded for advanced missions, and a considerable number of new ones undoubtedly will be added. Since much work has been and continues to be done on the guidance, navigation, and control functions, it was decided to emphasize the newer functions in this task. Brief descriptions of some expected new functions are given below.

4.1 Anticipated New Functions for Spaceborne Computers

a. System Checkout--Essentially continuous passive monitoring of all critical system parameters will be conducted throughout a mission. Before critical events such as thrusting, more detailed, active tests will be conducted. If a failure is detected, diagnostic testing will be able to isolate a fault to no more than a few replacable modules for electronic units. It is estimated that 2000-4000 test points will be available in flight. Software for monitoring and testing will require at least tens of thousands of memory locations. The onboard system will also be used for pre-launch checkout, and for remote checkout of the spacecraft from earth.

b. Experiment Data Management and Control--The checkout, calibration, and control of experiments will also utilize the onboard computers. Automated experiment control will include simple sequencing, control loops involving processing of experiment scientific data, and pointing and holding operations. Programmable formatting of experiment data will allow variations in sampling rates, selection of parameters, degree of scientific data processing, and level of data compression. The astronaut will be able to select data for display from a variety of experiments. He will also be able to do some preliminary analysis with the aid of curve-fitting, statistical filtering, and other mathematical programs.

c. Unmanned Probe Guidance--On planetary missions, unmanned probes may be launched from the manned spacecraft for atmospheric sampling, orbital photography, or retrieval of a surface sample. These probes would be checked out, launched, and guided with the aid of onboard computers. Computational complexity is estimated at several times that of the Apollo LM descent guidance programs (the most demanding inflight guidance program in Apollo).

d. Inflight Crew Skill Maintainance--Inflight simulators will be required to maintain crew skills which are infrequently used. Of critical importance are those associated with earth entry or planetary landings.

e. Astronaut-Computer Communications--With the increased emphasis on computer aids, the crew will be frequently communicating with the computer. Integrated situation displays, higher level languages, hard copy output and improved keyboards will be desirable to make the dialogue easier and more reliable.

4.2 Comments

One can imagine many other functions for which the computer system may be used. Examples are balancing of solar heat loads, pointing antennas, medical diagnosis, and even entertainment. In order to choose the functions to automate for a particular type of mission, it is necessary to quantify the computational and I/O requirements of each candidate function. The requirements must be translated into costs (weight, complexity, dollars, etc.) using the expected state-of-the-art available for that mission. The costs of automation must then be traded off (along with everything else) against mission goals.

A first cut at this process was attempted as part of Task 28, and led to the conclusion that all of the functions discussed in Section 4.1 could be implemented to some extent for a Manned Mars Flyby in the mid 1970's. Some form of each function is also applicable to earth-orbital missions. The groundwork for a second, more detailed analysis involving better definition of several functions (inflight training, computer aids for experiments, and man-machine communications) was started under Task 28 and is continuing as part of Bellcomm's general systems engineering support for advanced missions.

5.0 RECOMMENDATIONS FOR FURTHER STUDIES

The following recommendations for further study have resulted from Task 28:

1. The survey of the state-of-the-art of aerospace computers should be updated at least annually; it serves as a basis for predicting the future state-of-the-art and for feasibility analyses of new functions.

2. Another more quantitative iteration of ground data processing requirements should be performed. The requirements should be compared with the capabilities of a system based on the latest ground processing system planned for AAP. The study should determine what constraints the AAP ground system places on advanced missions or, alternatively, what augmentation would be required.

3. An attempt should be made to create improved mathematical models of computer-based systems for making configuration tradeoffs such as centralization/decentralization. An attempt to quantify or at least better define management problems for different configurations should also be made.

4. Techniques for making hardware-software tradeoffs should be explored. Although admittedly difficult to treat quantitatively, the potential payoffs are large.

5. Further definition of potential spaceborne computer functions is possible even at this point in time, and should be pursued. In particular, automated checkout, computer aids for experiments, inflight skill main-

tenance, probe guidance, computer-driven displays and computer-astronaut communications should be explored.

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REFERENCES

1. "The Flow of Data in Advanced Manned Missions," E. L. Gruman, B. H. Liebowitz, J. J. Rocchio, P. S. Schaenman, March 17, 1967, Bellcomm Memorandum for File, Case 228.

2. "Communications for Long Duration Missions," R. K. Chen, July 7, 1967, Bellcomm Memorandum for File, Case 228.

3. "Communications System Design for Manned Mars Flyby Mission," R. K. Chen and R. L. Selden, July 29, 1966, Bellcomm TM-66-2012-8, Case 103-2.

4. "State-of-the-Art of Aerospace Digital Computers, 1962-1967," D. O. Baechler, Bellcomm TM-67-1031-1, Case 228.

5. "Trip Report: Visit to Goddard Space Flight Center to Discuss Onboard Processor for Scientific Spacecraft," D. O. Baechler, August 25, 1967, Bellcomm Memorandum for File, Case 228.

6. "Trip Report: Spaceborne Experiments and Computers--Goddard Space Flight Center, September 25, 1967," P. S. Schaenman, November 6, 1967, Bellcomm Memorandum for File, Case 228.

7. "Functional Requirements for Spaceborne Computers on Advanced Manned Missions," E. L. Gruman and P. S. Schaenman, October 24, 1966, Bellcomm TM-66-1031-2, Case 228.

APPENDIX

The documents described below are the memoranda, papers, and trip reports which were produced under Task 28.

Memoranda

1. "Functional Requirements for Spaceborne Computers on Advanced Manned Missions," E. L. Gruman, P. S. Schaenman, Bellcomm TM-66-1031-2, October 24, 1966, discusses functions which will require support from the onboard computer system. It includes Guidance and Navigation, attitude control, automated checkout, inflight crew training, control and data management of experiments, displays, unmanned probe operations, and computer-astronaut communications.

2. "Review of Proposed AAP Experiment 'Long Range High Frequency Communications'," R. L. Selden, Bellcomm Memorandum for File, February 10, 1967, reviews a proposed long range, high frequency radio communications experiment.

3. "The Flow of Data in Advanced Manned Missions," E. L. Gruman, B. H. Liebowitz, J. J. Rocchio, P. S. Schaenman, Bellcomm Memorandum for File, March 17, 1967, discusses the flow of data from sources in space to ultimate users on the ground for three missions: 1) Mars Flyby, 2) Earth-Orbital/Earth Resources and Meteorology, 3) Earth-Orbital/Astronomy. Estimates are given for the types, rates, and quantities of data generated and for the amount of spaceborne data storage required. Factors which must be considered for future ground systems are presented along with a description of the ground systems used in Apollo. A brief discussion of spacecraft-earth communications is included.

4. "State-of-the-Art of Aerospace Digital Computers, 1962-1967," D. O. Baechler, Bellcomm TM-67-1031-1, June 27, 1967, describes characteristics of 40 aerospace computers. Trends in overall design, computational speed, weight, power, and volume are also discussed.

5. "Communications for Long Duration Earth Orbital Missions," R. K. Chen, Bellcomm Memorandum for File, July 7, 1967, discusses use of the present Manned Spaceflight Network and a projected communications satellite network for transferring wideband information between a spacecraft and earth.

Published Papers

1. "Functional Requirements for Spaceborne Computers Used on Advanced Manned Missions," E. L. Gruman and P. S. Schaenman, Bellcomm Memorandum for File, was presented at the Spaceborne Multiprocessing Symposium, Boston, Massachusetts, (Sponsored by NASA Electronics Research Center), October 31, 1967, and is essentially identical to Memorandum #1.

2. "The Role of Spacecraft Computers on Advanced Manned Missions," E. L. Gruman and P. S. Schaenman, Bellcomm Memorandum for File, was presented at the Fourth Space Congress, Canaveral Council of Technical Societies, Cocoa Beach, Florida, April 6,1967, and is essentially identical to Memorandum #1.

3. "State-of-the-Art of Aerospace Digital Computers, 1962-1967," D. O. Baechler, Bellcomm Memorandum for File, has been published in the IEEE Computer Group News, January, 1968, and is essentially identical to Memorandum #4.

Trip Reports

1. "Trip Report: "Stepping Stones to Mars", Meeting in Baltimore, Maryland, March 28-30, 1966," E. L. Gruman, Bellcomm Memorandum for File, April 6, 1966, reports the agenda and topics of interest for an AIAA-sponsored symposium on Mars Missions.

2. "Trip Report: Visit to ERC for Briefing on Advanced Computer Studies," D. O. Baechler, Bellcomm Memorandum for File, April 19, 1967, reports meetings at which Bellcomm and the NASA-Electronics Research Center exchanged information on aerospace computer research in progress and planned.

3. "Trip Report: Visit to Navy Department, Washington, D. C.," J. J. Rocchio, Bellcomm Memorandum for File, June 27, 1967, reports a meeting to discuss computer-based systems used in submarines.

4. "Trip Report: Visit to Johnsville Naval Air Development Center," J. J. Rocchio, Bellcomm Memorandum for File, June 26, 1967, reports meetings to discuss the computer-based system called the "Integrated Helicopter Avionics System."

5. "Trip Report: Visit to Air Force Systems Command to Discuss Computer System Design," D. O. Baechler, Bellcomm Memorandum for File, June 28, 1967, reports a meeting to discuss computers used in the F-111 and C-5A aircraft.

6. "Trip Report: Visit to Goddard Space Flight Center to Discuss On-Board Processor for Scientific Space-craft," D. O. Baechler, Bellcomm Memorandum for File, August 25, 1967, reports a meeting to discuss the general purpose Onboard Processor being developed by the NASA Goddard Space Flight Center.

7. "Trip Report: Visit to Environmental Sciences Administration, Boulder, Colorado," D. O. Baechler and R. H. Hilberg, Bellcomm Memorandum for File, October 30, 1967, reports a meeting to discuss the data collection system used for data on ionospheric disturbances and solar activity.

8. "Trip Report: Spaceborne Experiments and Computers--Goddard Space Flight Center, September 25, 1967," P. S. Schaenman, Bellcomm Memorandum for File, November 6, 1967, reports meetings to discuss applications of spaceborne computers to experiments.